Geological and mineralogical investigations of the lithologies and their weathering products in a study area south-west of the field station “La Gamba“, Golfo Dulce, Costa Rica

Investigación geológica y mineralógica de las rocas y sus productos de meteorización, en un área al suroeste de la estación “La Gamba”, Golfo Dulce, Costa Rica

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Abstract: The study area belongs to the Golfito terrain. By geological mapping and mineralogical analyses five sedimentary lithologies can be distinguished: fine-grained greenish tuffitic siliciclastics (1), semi-consolidated sands (2), blue-grey micritic limestone (3), red mudstones (4) and greyish clays (5). A significant volcanoclastic input for all siliciclastic sediments is indicated by the presence of smectite. Additionally, basalt, basaltic tuffs and basaltic volcanic breccias can be observed. Most of the study area consists of fine-grained greenish tuffitic siliciclastics (lithology 1), generally composed of smectite and quartz as the main constituents, with small proportions of illite. In some samples varying amounts of zeolite (probably of heulandite-clinptilolite series), plagioclase and clinopyroxene were detected by X-ray diffractometry. Lithologies 2 to 5 are intercalated in one section of about 10 m. The mircofossil content of the limestone (3) suggests a Cretaceous age. Albitisation of plagioclase crystals together with the occasional occurrence of calcite cement indicates marine influence on the basaltic lavas. Hydrothermal activity is suggested by an iron-rich talc mineral observed in samples of basalt and basaltic tuff. The weathering products (partly laterites) developed from these lithologies can be distinguished by their quartz content. Soils overlying the widespread greenish tuffitic siliciclastics (lithology 1) are quartz-bearing, whereas those overlying basaltic rocks are generally quartz-free. In most soil samples, the dominant mineral phase is represented by interstratified kaolinite-smectite. In some samples, disordered kaolinite is predominant. The main crystalline iron minerals are goethite and hematite. A member of the magnetite/maghemite group is present in some samples. A lesser degree of weathering is indicated in some samples by the presence of smectite and feldspar. In a few samples, very intensive weathering is indicated by small amounts of gibbsite. Recent volcanic influence is proven by the occurrence of amphibole in the uppermost parts of some weathering profiles.

Key words: Golfito Terrain, volcanic rocks, volcanoclastics, sedimentary rocks, weathering, clay mineralogy.

Resumen: El área estudiada se localiza en la zona de Golfito. Con base en mapas geológicos y análisis mineralógicos, se han podido distinguir cinco litologías sedimentarias, a saber: (1) tufitas siliciclásticas verdosas de grano fino; (2) arenas semiconsolidadas; (3) caliza micrítica gris azulada; (4) lodolitas rojas; (5) arcillas grisáceas. La presencia de esmectita en todos los sedimentos siliciclásticos indica la existencia de una importante pero variable cantidad de material volcaniclástico. Además, basaltos, tufas y brechas basálticas, pueden ser observados. La mayor parte del área está conformada por materiales siliciclásticos tufíticos verdosos de grano fino (litología 1), generalmente compuestos de esmectita y cuarzo como componentes principales, con una pequeña porción de ilita. Análisis por difractometría de rayos-X de algunas muestras indicaron cantidades variables de zeolitas (probablemente de la serie heulandita-clinoptilolita), plagioclasas y clinopiroxeno. Las litologías 2 a 5 se encontraron intercaladas en una sección de unos 10 m. La microfauna en la caliza micrítica (litologiá 3) indica un edad Cretácico. La albitización de algunas plagioclasas demuestra la influencia de agua marina en las rocas basálticas, lo cual corresponde a la ocurrencia ocasional de cemento de calcita en estas rocas. La presencia de minerales de talco enriquecido en hierro observados en muestras de basaltos y tufas basálticas, indican una cierta actividad hidrotermal. Los productos de meteorización (parcialmente lateritas) desarrollados de estas litologías se pueden distinguir por su contenido de cuarzo. Los suelos que sobreyacen la ampliamente distribuida tufita siliciclástica verdosa (litología 1) contienen cuarzo; en cambio, aquellos que sobreyacen a las rocas basálticas son generalmente libres de cuarzo. En muchas muestras de suelos la fase mineral dominante la representa el interestratificado caolinita-esmectita. En otras muestras una caolinita desordenada ocurre como la fase dominante. Los principales minerales de hierro son goethita y hematita. En algunas muestras es posible observar minerales del grupo magnetita/maghemita. Un bajo grado de meteorización se indica en algunas muestras por la presencia de esmectita y feldespato. Unas pocas muestras revelan un mayor grado de meteorización, indicado por pequeñas cantidades de gibbsita. Una influencia volcánica reciente se comprueba por la ocurrencia de anfíboles en las partes superiores de algunos perfiles.

Palabras clave: Terreno de Golfito, rocas volcánicas, volcanoclásticas, rocas sedimentarias, meteorización, mineralogía de arcillas.

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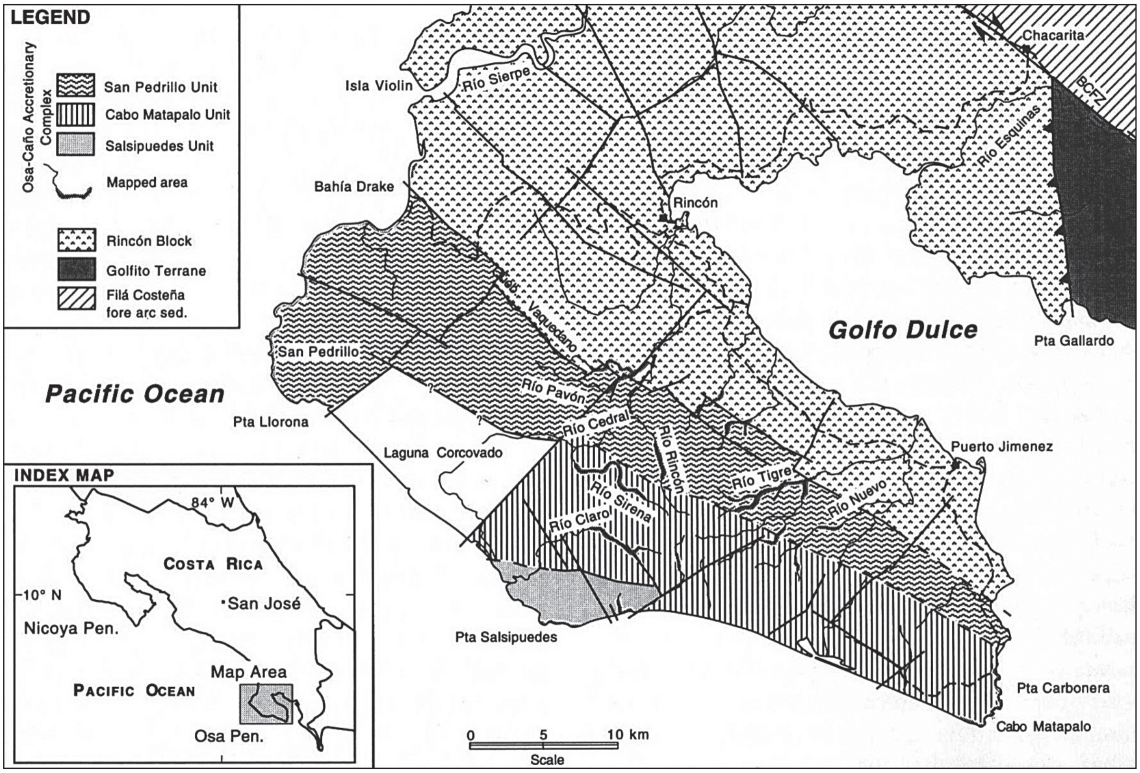


Fig. 1: Pre-Neogene tectonic units of the Golfo Dulce region (from DiMarco et al. 1995).

Introduction

The investigated area lies south-west of the La Gamba field station and is bordered by the "Fila path" (5 km long path starting and ending near the field station). Within the area, all outcropping rocks and weathering products were geologically mapped and samples were collected for laboratory analyses, particularly X-ray diffractometry (XRD). Additionally, selected samples were analysed by X-ray fluorescence. Thin sections of some samples were studied by polarising microscopy and cathodoluminescence microscopy. An overview of the applied analytical techniques is given in the chapter "Laboratory procedures". The results presented here are based on the diploma thesis of Scheucher (2006).

Regional geological setting

According to DiMarco et al. (1995) four pre-Neogene tectonic units are present in the Golfo Dulce region (Fig. 1).

The southern fringe of the Osa Peninsula is represented by strongly deformed, late Cretaceous to Micoene sediments of the Osa-Caño Accretionary Complex, consisting of turbidites and other pelagic and hemipelagic sediments, carrying boulders of oceanic basalts and various sedimentary rocks (DiMarco 1994, DiMarco et al. 1995).

The Rincón Block forms most of the land area bordering the Golfo Dulce and comprises basaltic basement with overlying Cretaceous to Eocene sediments (DiMarco 1994).

To the north-east of the Rincón Block are fluvatile, lacustrine and marine siliciclastics and carbonates of the Fila Costeña fore arc sediments (Yuan & Lowe 1987).

The La Gamba field station and thus the study area are located within the Golfito Terrain, which flanks the Rincón Block to the east and the Filá Costeña fore arc sediments to the south-west (Fig. 1). Within this terrain three geologic units can clearly be distinguished (DiMarco 1994, Fig. 2). The igneous basement is formed by massive oceanic basalts and dolerites, sometimes occurring in the form of pillows. This basement is overlain by sediments and volcanic rocks of the Golfito Formation. Pelagic carbonates with minor occurrences of volcanoclastic sediments are intercalated with doleritic and basaltic flows and occasionally basaltic breccias. The absence of lavaflows marks the base of the Quebrada Achiote Formation, the uppermost unit of the Golfito Terrain. Large quantities of volcanoclastic sediments with few intercalations of pelagic limestones and basaltic breccias characterise this formation. The Fila Gamba Member, consisting of tuffites and tuffs, is the uppermost unit of the Quebrada Achiote Formation. The stratigraphy of the Golfito Terrain, as stated by DiMarco (1994), is shown in Figure 2.

Field survey (sampling)

Detailed geological mapping was conducted during April and May 2004. All paths surrounding the field station were mapped and transferred onto a topographic map. Primary lithologies were examined from natural

and man-made exposures (the latter formed when the paths were cut into the rain forest). Even with intensive tropical weathering, some of the outcrops provided important information on such geological features as stratification and jointing. Representative samples from various lithologies were collected. For the interpretation of the weathering products, information on the subsurface stratigraphy was obtained via cores from an auger drill. Additionally several trenches were dug for further sampling.

Laboratory procedures

All samples were analysed by means of XRD, using a Philips Xpert system. Preparation of the samples as oriented mounts for XRD analyses included air-drying, disaggregation to ca. 5 µm and making a paste (0.085 g powder mixed with 0.045 ml distilled water). The paste was smeared into a groove (depth 100 µm, width corresponding to that of the primary beam) of a glass sample holder ("smear-on-glass", for more details see VORTISCH 1982). Because of the reaction during drying, some smectite-rich samples had to be prepared without adding water. The oriented mounts were measured sequentially in an untreated condition, after treatment with ethylene glycol (EG) (according to BRUNTON 1955) and after thermal treatment (2 hours) at 350°C and 550°C. These treatments are standard procedures in clay mineralogy and necessary to distinguish clay minerals with sufficient certainty (e.g. VORTISCH 1982). For reasons of clarity, all four measurements of one sample were combined in one figure (from bottom to top: untreated / EG-saturated / 350°C treated / 550°C treated, see Fig. 4). Determination of interstratified clay minerals followed MOORE & REYNOLDS (1997).

In order to determine changes in the chemical composition during weathering, selected samples were analysed by means of X-ray fluorescence (XRF). Sample preparation for XRF analysis includes grinding to <100 µm, drying at 105°, and heating to 1000°C. One gram of heated powder is mixed with six grams of lithium tetraborate (flux agent) and melted. The melt is poured into a platinum mould and the resulting glass tablet is used for analysis.

Thin sections of selected samples were examined by polarising microscopy and cathodoluminescene microscopy (CL; equipment: CITL Mk 3). Polished thin sections were applied for CL-microscopy.

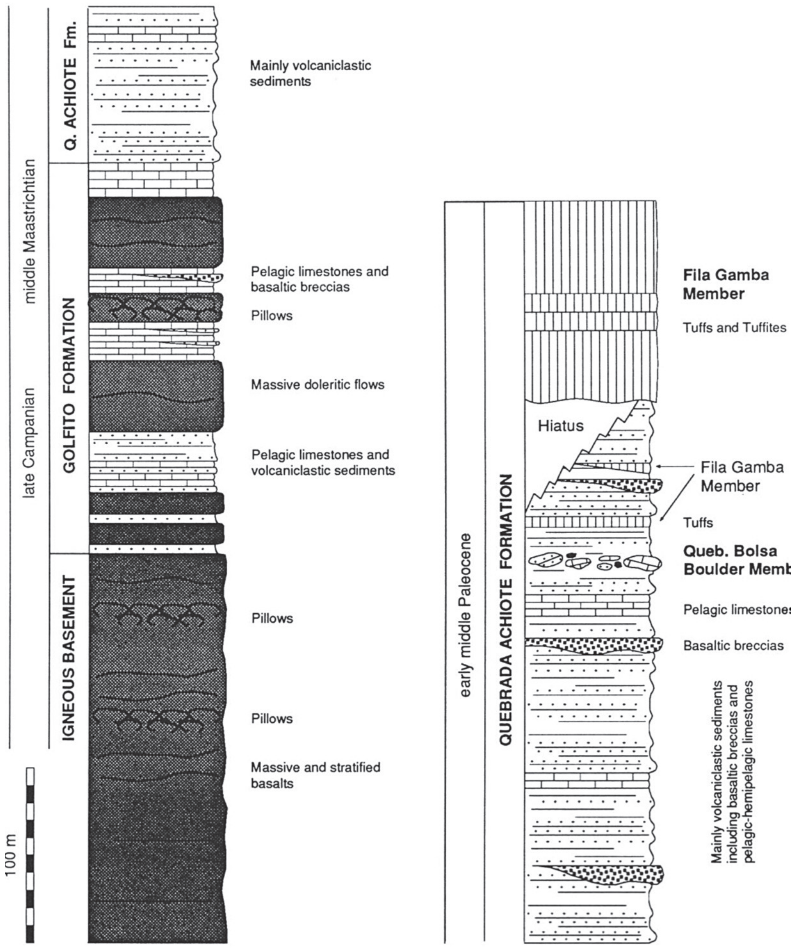


Fig. 2: Stratigraphy of the Golfito Terrane (from DIMARCO 1994).

Results

Primary lithologies (parent rocks)

On the basis of field survey and X-ray diffractometry five distinct lithologies were recognised:

Tuffite

This rock type is the most prevalent in the investigated area. In outcrops, the tuffites show variations in colour, bedding and grain size. The colour ranges from light green to light blue-green. Regarding grain size, these tuffites appear as unconsolidated to semi-consolidated clayey to silty sediments. Grain size as well as bedding vary over short distances. A relationship between grain size and bedding is evident: the finer grained tuffites show mm-lamination whereas the coarser ones are thickly bedded to massive. In thin sections of the coarser grained tuffites (Fig. 3), grains of quartz (up to 100 µm) and glauconite (a green Fe/Mg-rich 2:1 clay mineral), and radiolarians can be identified. The occurrence of glauconite and radiolarians proves the marine depositional environment of these rocks.

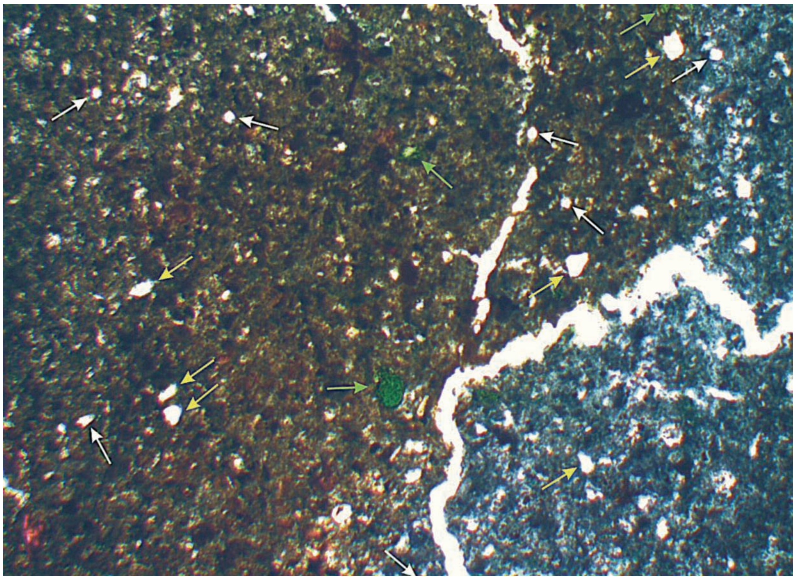


Fig. 3: Thin section of a coarse-grained green tuffite (quartz: yellow arrows, glauconite: green arrows, radiolarians: white arrows; length of image: 2.67 mm, plane-polarised light).

In addition to the macroscopic characteristics, differences in the mineralogical composition of the tuffites also exist. All analysed samples contain varying amounts of smectite (with some samples showing partial chloritisation of smectite), quartz and illite (Fig. 4). Chlorite was probably formed by chloritisation of smectite (loss of expansibility) through uptake of Al^{3+}- or Fe^{3+}-hydroxide in the interlayer space (soil chlorite in the sense of SCHWERTMANN & STANJEK 2002). It shows low crystallinity and low thermal stability (amorphous after heat treatment at 550°C/2 h). Besides the occurrence of illite as a clastic component, diagenetically formed illite (1M-illite) has been found in some samples.

Additionally, some of the samples contain anatase, plagioclase and zeolite (presumably of the heulandite-clinoptilolite series). In one sample, small amounts of clinopyroxene were found whereas another sample contains noticeable amounts of chlorite. The mineralogical composition of a zeolite-bearing tuffite is shown in Figure 5. The discernibility between chlorite and smectite after EG- and thermal treatment is clearly noticeable.

The chemical analysis of a sample containing smectite, illite, quartz and anatase shows an Fe-content (Fe_2O_3) of approx. 8.5% w/w. Because smectite is the only iron bearing mineral in this sample it must be of nontronitic nature. Dioctahedral smectite (nontronite) and zeolite (especially of the heulandite-clinoptilolite series) are common mineral phases formed by diagenetic transformation of glass-rich volcanic ashes in marine environments, as observed, for instance, in Costa Rica by VORTISCH (1990).

Basic tuff

In the studied outcrops these tuffs appear as brown-coloured, unconsolidated sands. They form homogeneous sequences with thicknesses of several metres without any sedimentary structures. Figure 6 shows the appearance of the basic tuffs in the field. An erosional unconformity between the green tuffites (lithology 1.1) and the overlying brown tuffs could be observed in one section (Fig. 7).

The basic nature of these tuffs is shown by their mineralogical composition. The predominant mineral phases are smectite and plagioclase. Microprobe analyses of the plagioclases show a Na:Ca ratio of about 1:1, signifying that their composition is located at the andesine/labradorite boundary. Clinopyroxene, orthopyroxene, and olivine were also observed. The presence of interstratified kaolinite-smectite indicates the beginning of weathering. Due to decreasing weathering intensity with depth, the amount of this clay mineral decreases downwards in weathering profiles. Samples taken from deeper parts of some sections, additionally contain an iron-rich talc mineral, an indicator of possible hydrothermal influence (see also below, Figs. 21 and 22). Figure 8 represents the mineralogical composition of one sample of the basic tuffs. XRF analyses provide SiO_2 (about 50% w/w) and MgO (6% w/w) data which are typical for mafic rocks.

The mineralogical composition of the tuffs directly overlying the green tuffites differs from the composition described above with respect to the presence of quartz and the absence of orthopyroxene and olivine.

Sedimentary sequence at location no. 5

Only at one location (no. 5) within the investigated area, a complex sequence of sedimentary rocks and unconsolidated sediments was detected. The base of this sequence is formed by a one metre-thick layer of light grey-coloured silty material, overlain by brown sand of several metres thickness (Fig. 9). The contact between these two layers is irregular and seems to be disturbed (tectonic processes or sliding?). The sand shows intercalations of grey silt and is overlain by a one metre thick layer of a brown, massive, silty to clayey, consolidated sediment (mudstone) with red-coloured coatings on fissures. Between this mudstone and the overlying grey clay, a 10 cm thick intercalation of a bluish-grey coloured limestone occurs (Fig. 10; XRD: essentially calcitic, minor amounts of quartz). This limestone is overlain by a grey-coloured clay of about 20 cm thickness. Above this clay follows a 30 cm thick layer of brown sand. The spatial grain size distribution of this sand indicates graded bedding: normal grading (i.e. upward-decreasing grain size) in the lower part and inverse grading in the upper one.

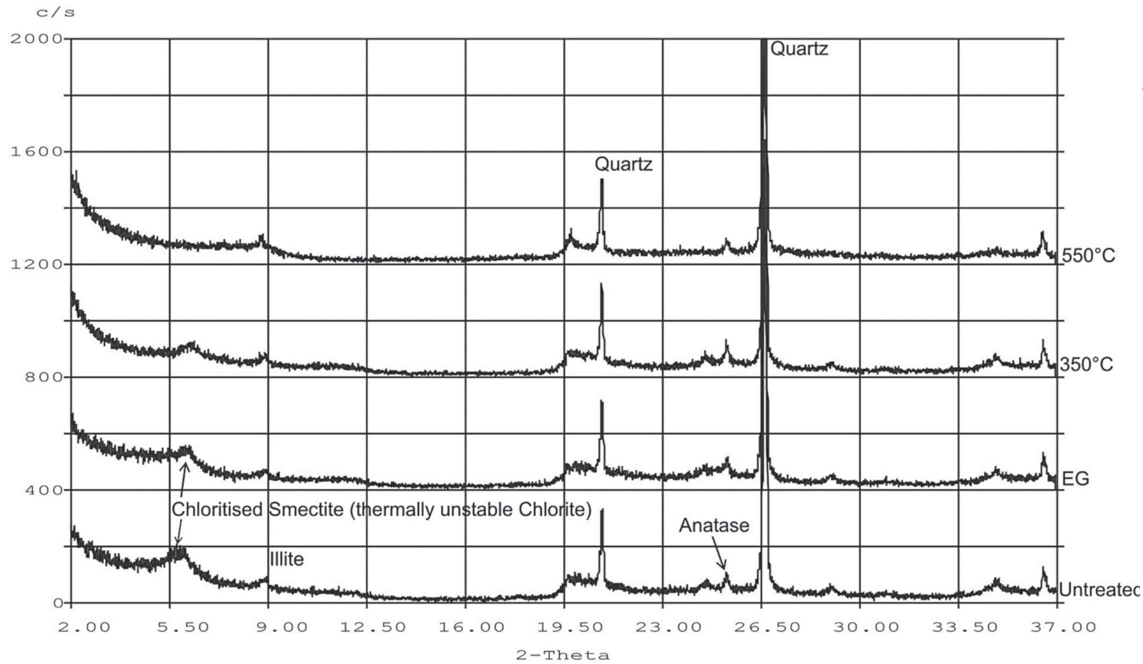


Fig. 4: Mineralogical composition of a laminated, light green tuffite (sample no. 1 in Fig. 25).

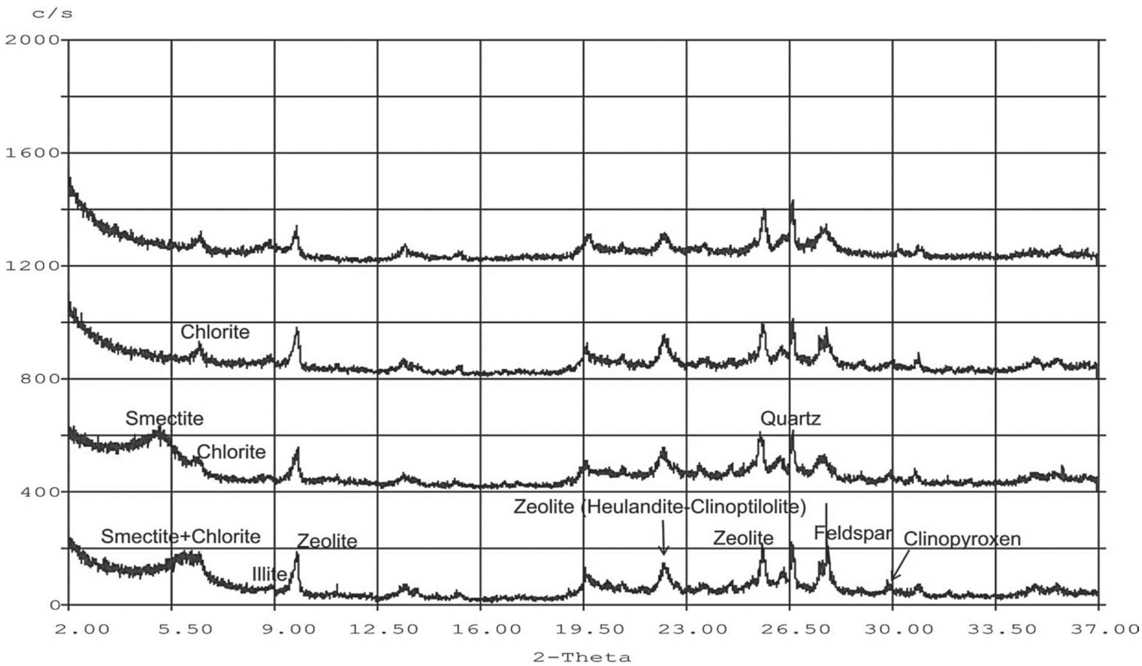


Fig. 5: Mineralogical composition of a coarse-grained, bedded tuffite (sample no. 2 in Fig. 25).

On the basis of microscopical investigation, the limestone was classified as wackestone to packstone (according to the nomenclature of DUNHAM 1962). The microfauna suggests a Cretaceous age (Axel von Hillebrandt, pers. comm.). It is represented by radiolarians (calcitised) and planctonic foraminifera.

The volcanoclastic influence on the siliciclastic sediments of this sequence can clearly be seen in the mineralogical composition, as all analysed samples show high amounts of smectite, resp. smectite-rich interstratified clay minerals as illite-smectite and kaolinite-smectite. Moreover, considerable amounts of quartz and varying proportions of feldspar (mainly plagioclase) occur. Some samples additionally contain zeolite and clinopyroxene. Clay mineralogy appears to be quite complex in some samples of the sedimentary sequence, as shown for the grey-coloured clay in Figure 11.

Massive basalt and basaltic volcanic breccia

Besides the brown basic tuff mentioned above, there are two other types of basic volcanic rocks in the investigated area: dark-coloured, massive volcanites and volcanic breccias. Due to their resistance to weathering, the massive volcanites form a distinctive morphological ridge (location no. 9). Macroscopically, these rocks are very fine-grained without visible phenocrysts. Under

Fig. 6: Outcrop of basic tuff (location no. 3 in Fig. 25).

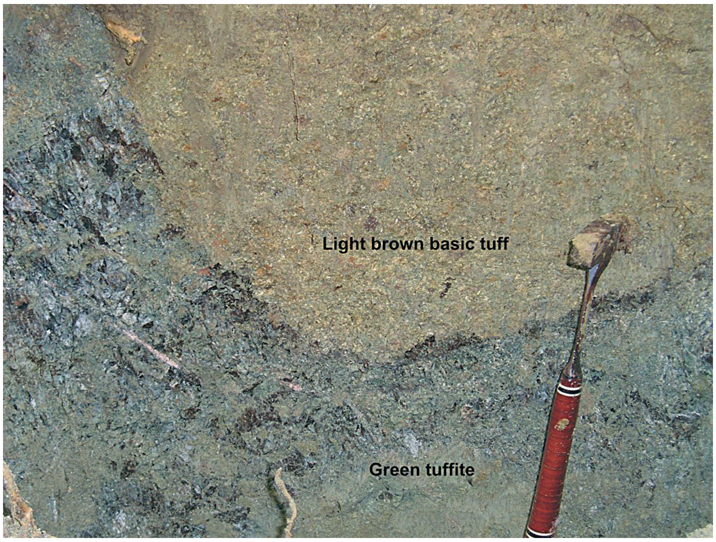


Fig. 7: Erosional contact between green tuffite and basic tuff (location no. 4 in Fig. 25).

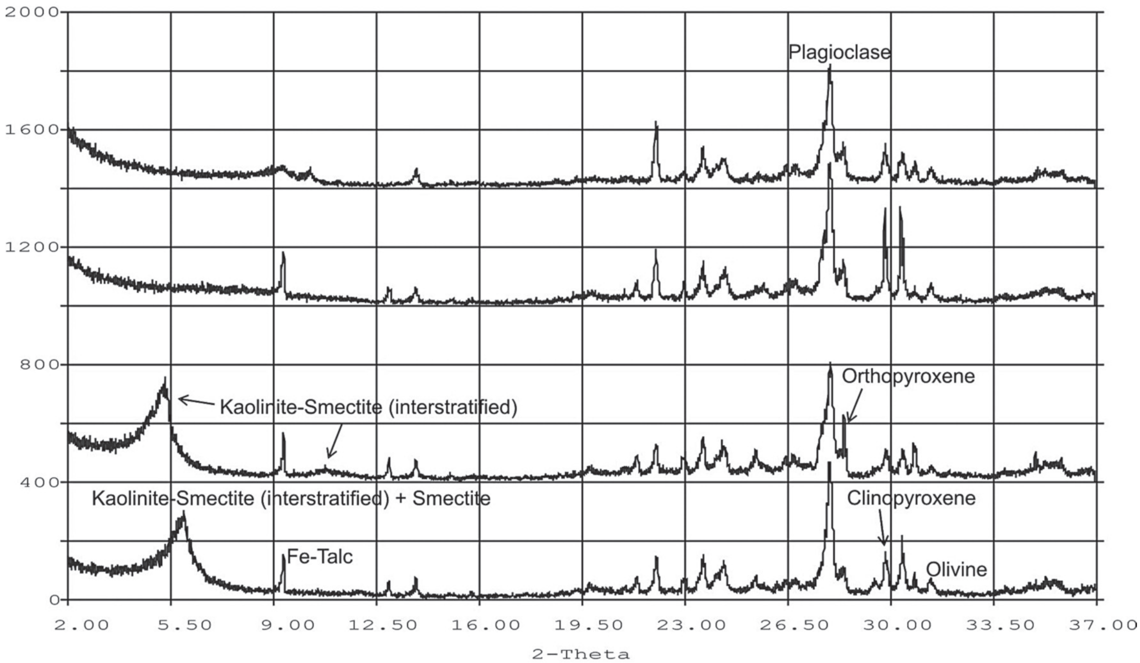


Fig. 8: Mineralogical composition of a sample of basic tuff (location no. 3 in Fig. 25, sampling depth: 2.3 m).

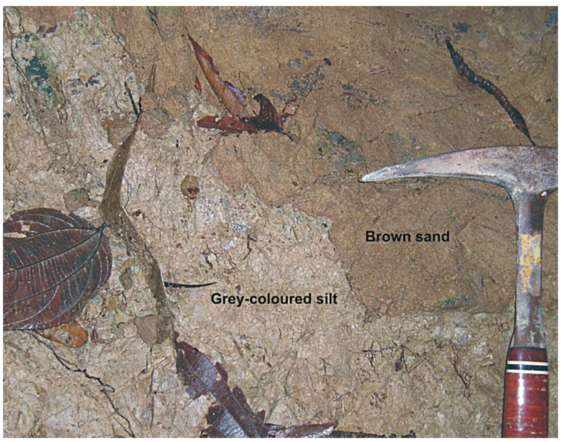


Fig. 9: Brown sand overlying grey-coloured silt (location no. 5 in Fig. 25).

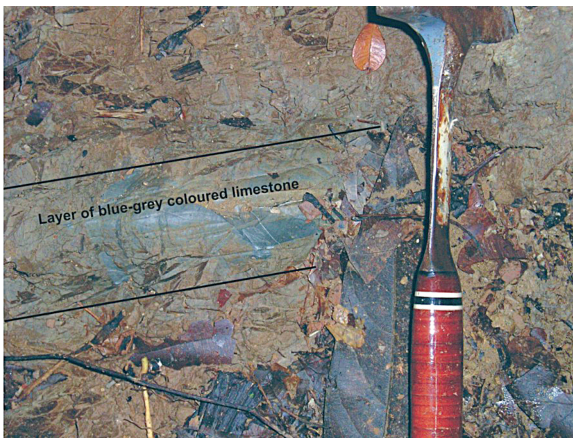


Fig. 10: Carbonate layer within the sedimentary sequence (location no. 5 in Fig. 25).

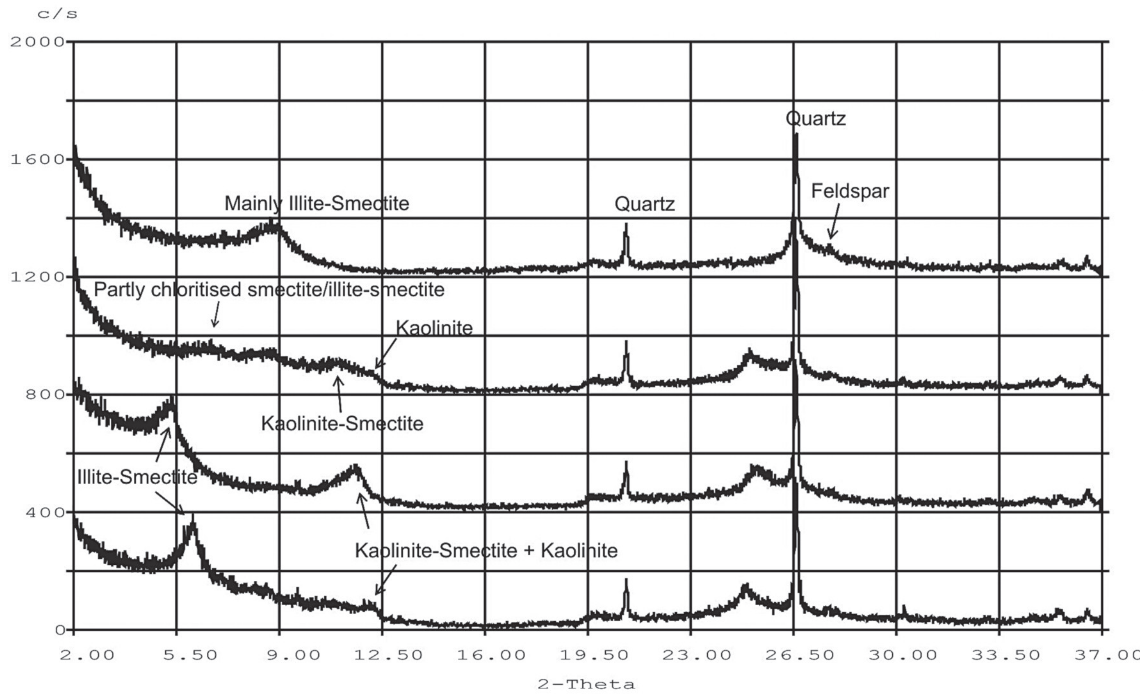


Fig. 11: Mineralogical composition of a grey clay within the sedimentary sequence (sample from location no. 5 in Fig. 25).

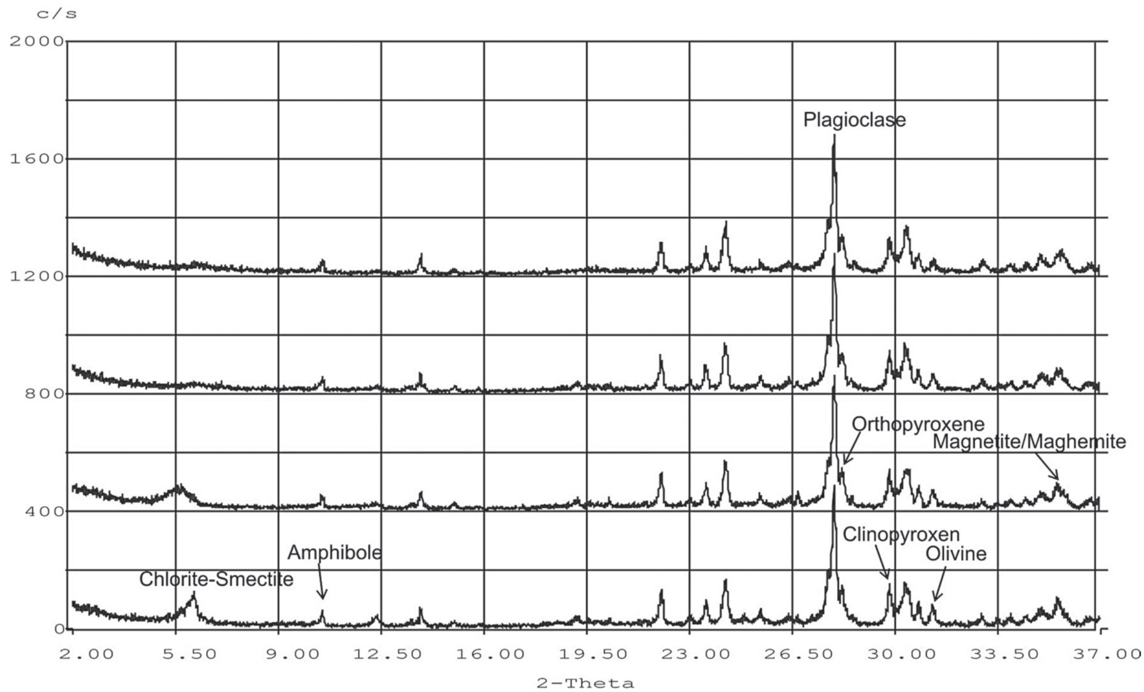


Fig. 12: Mineralogical composition of a volcanic breccia (sample from location no. 6 in Fig. 25).

the microscope, they show a hypocrystalline fabric. Lath-shaped plagioclases are embedded in a very fine-grained matrix. Isolated grains of olivine and clinopyroxene can also be observed. Additionally, orthopyroxene was detected by XRD. Sometimes tridymite and zeolite occur as fillings in joints and cracks. On the basis of Na_2O, K_2O, and SiO_2 content, these volcanites can be classified as basalts.

The volcanic breccias consist of a variety of different-coloured clasts, all of which are of volcanic origin. The mineralogical composition of the breccias is comparable to those of the massive basalts. Both rock types contain noticeable amounts of smectite (occasionally chlorite-smectite). Microprobe analyses of some plagioclases show that they have undergone albitisation, a common process in marine environments. Traces of magnetite/maghemite are always present. As a representative example of these basic volcanic rocks, the X-ray diffraction patterns of an amphibole-bearing volcanic breccia are shown in Figure 12.

Some clasts contain significant amounts of volcanic glass. The glass grains show signs of transformation into

Fig. 13: Thin section of volcanic breccia, showing calcite cementation (length of image: 6.85 mm, plane-polarised light).

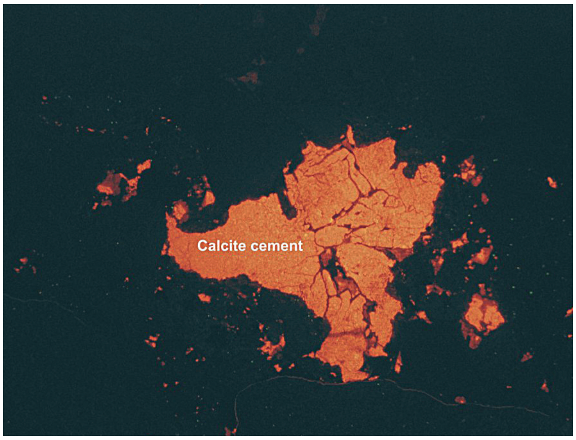


Fig. 14: CL image from the same area as Fig. 13, showing typical calcite CL colour (length of image: 6.85 mm).

Fig. 15: Lateritic weathering profile (quartz-bearing) in a pit (location no. 7).

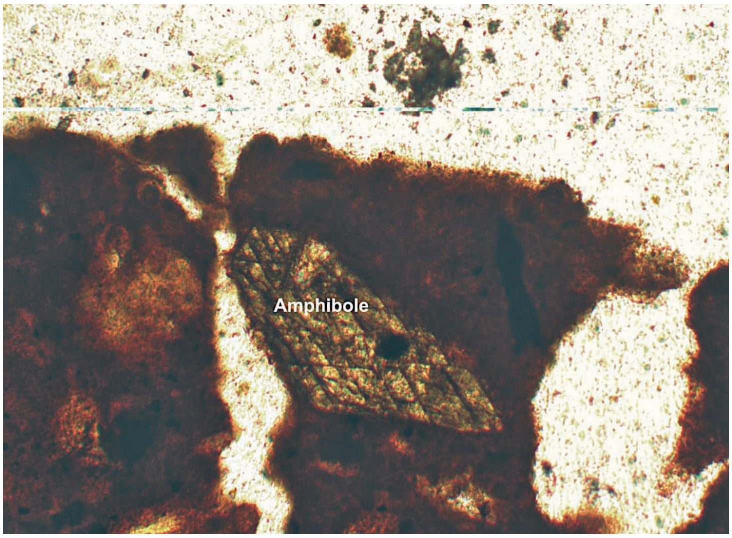


Fig. 16: Fresh amphibole in sample of quartz-bearing lateritic weathering product (sampling ca. 0.3 m below surface, length of image: 0.65 mm, plane-polarised light, location no. 7)

a green-coloured mineral phase (possibly nontronite or chlorite). Nontronite, an iron-rich dioctahedral smectite, often found in altered basaltic rocks, is indicated by XRD, as all analysed samples contain smectite. Moreover, radially crystallised zeolite occurs. XRD analyses indicates the occurrence of analcime (a Na-zeolite). The radial fabric is typical for rapid cooling. Structure and chemistry of this zeolite suggest deposition in a marine environment. Another indication for marine influence on the volcanic breccia is the occurrence of calcite cement (although calcite-free samples exist as well), because formation of calcite is less probable under tropical weathering conditions (Figs. 13 and 14). The CL photo (Fig. 14) shows the typical orange CL colour of calcite.

Weathering products (laterites)

Corresponding to the latitude of the Golfo Dulce region, most of the investigated area is covered by thick, intensively red-coloured weathering products. The appearance of these weathering products in the field is shown in Figure 15. Some of them can be classified as laterites in the sense of SCHELLMANN (1986). On the basis of XRD analyses two different types of weathering products can be distinguished.

Quartz-bearing weathering products/laterites

Nearly all of the quartz-bearing weathering profiles contain small, light green rock pieces in the deeper parts. These pieces are considered to be remnants of the underlying green tuffites. Therefore, the tuffites can be seen as parent rocks for these weathering products. Samples taken from the most weathered parts can be referred to as laterites due to their mineral composition. Generally, the dominant mineral phase is interstratified kaolinite-smectite, predominantly consisting of kaolinite layers (ranging from ca. 77% in deeper sections to ca.

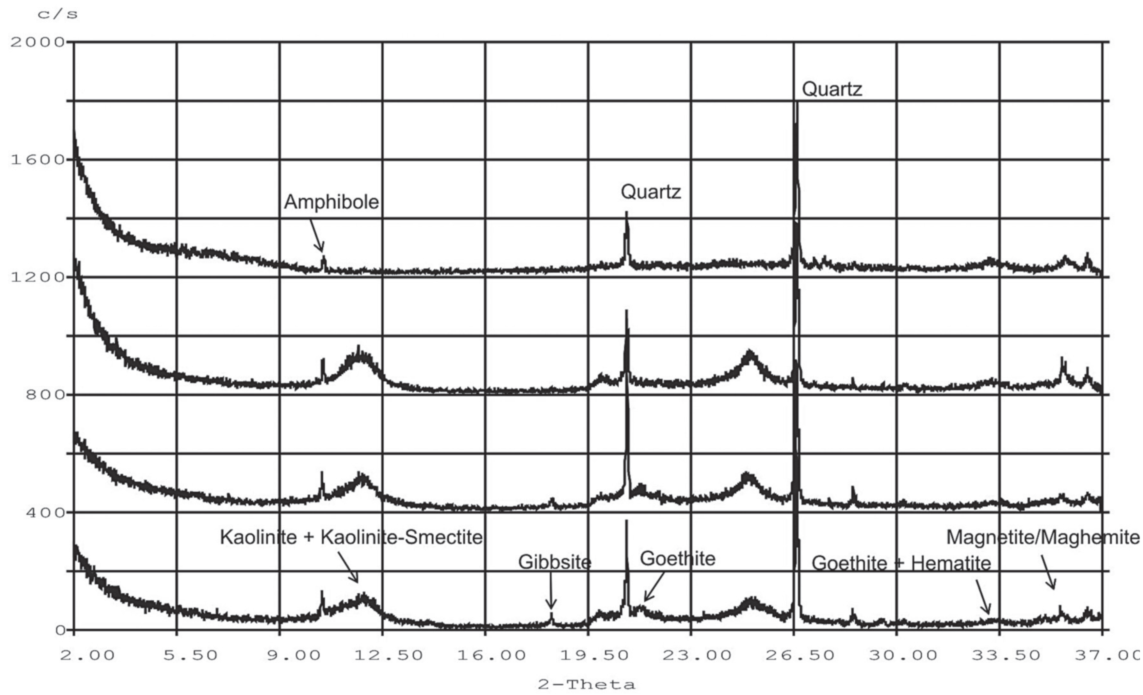


Fig. 17: Mineralogical composition of quartz-bearing laterite, sample depth: 0.3 m (location no. 7 in Fig. 25).

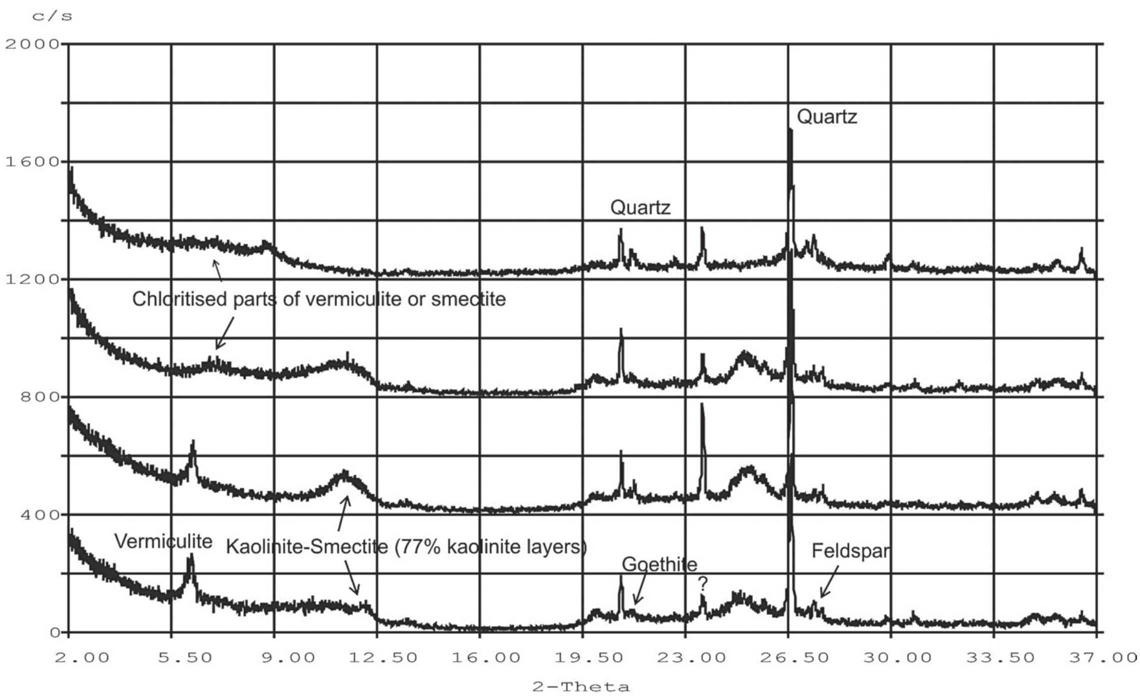


Fig. 18: Mineralogical composition of quartz-bearing weathering product, sample depth: 2.3 m (location no. 8 in Fig. 25).

94% near the surface). Besides kaolinite-rich interstratified kaolinite-smectite, disordered kaolinite (possibly metahalloysite) occur in the uppermost parts of lateritic weathering profiles. As mentioned above, in all sections considerable amounts of quartz could be detected. The presence of small amounts of gibbsite in the upper parts of some sections indicates very intensive tropical weathering. The occurrence of hematite and goethite is typical for tropical soils. In one profile near the field station traces of anatase were found. The less weathered parts also contain residues of the primary, resp. diagenetically or hydrothermally formed mineral assemblage (smectite, illite and feldspar). In one section, smectite is replaced by non-expanding vermiculite in the deeper parts (Fig. 18). Traces of magnetite/maghemite are present in some profiles. As already described by PAMPERL (2001a) noticeable amounts of an amphibole mineral are present near the surface in some sections. The amphibole grains can be up to 300 µm in size, as shown in Figure 16. These relatively fresh amphibole grains indicate recent to subrecent volcanoclastic influence.

The mineralogical composition of two selected samples of quartz-bearing weathering products are shown in

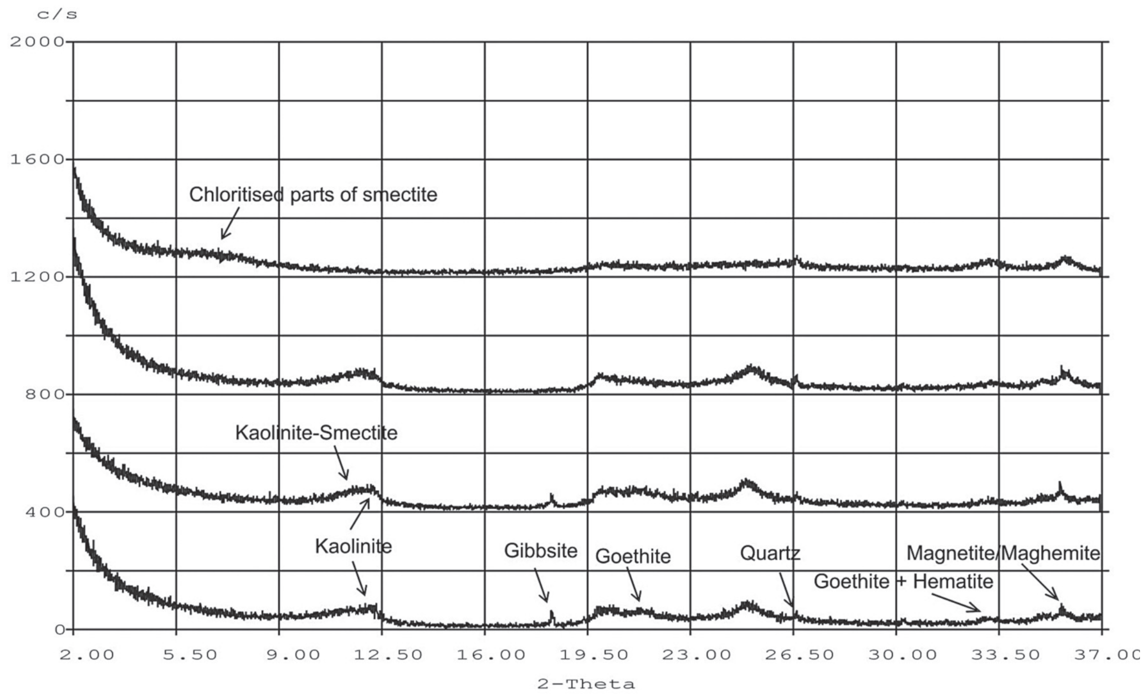


Fig. 19: Mineralogical composition of sample 1, quartz-free laterite (location no. 9 in Fig. 25, 0.2 m below surface).

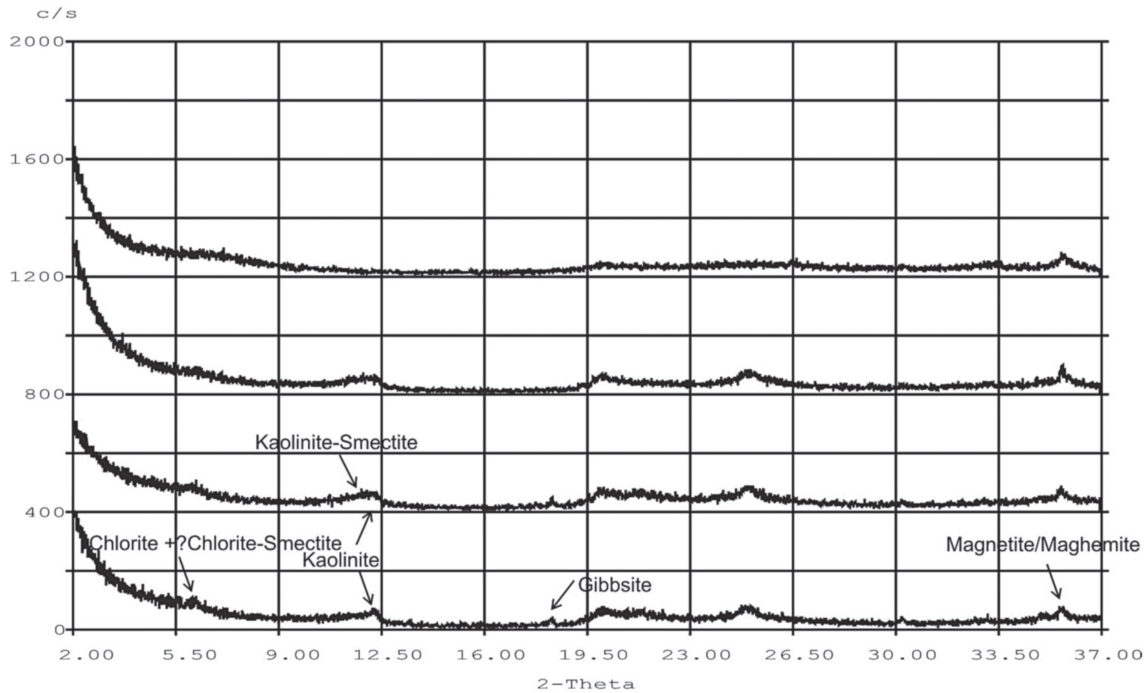


Fig. 20: Mineralogical composition of sample 2 (location no. 9 in Fig. 25, 0.6 m below surface).

Figures 17 and 18 (Figure 17 representing the more intensively weathered material, occurrence of gibbsite).

XRF analyses of one profile of the quartz-bearing weathering products (location no. 7) showed that samples taken near the surface (more intensively weathered) are depleted in alkaline and earth-alkaline elements (Na_2O, K_2O, CaO, and MgO) and enriched in immobile elements like Al_2O_3 and Fe_2O_3 . However, the presence of an amphibole mineral near the surface (Figs. 16 and 17) falsifies the results of XRF analyses with respect to alkali and alkaline earth elements.

Quartz-free weathering products/laterites

Macroscopically, these laterites can hardly be distinguished from the quartz-bearing laterites. In the field they appear more auburn than red and more clayey than the quartz-bearing laterites. No fragments of the parent rock have been observed in any section. So, these weathering products could have been developed from the basic tuffs, basalts or volcanic breccias. Some differences regarding mineralogical composition can be seen. Most noticeable is the absence of quartz. Magnetite/maghemite occurs with higher proportions than

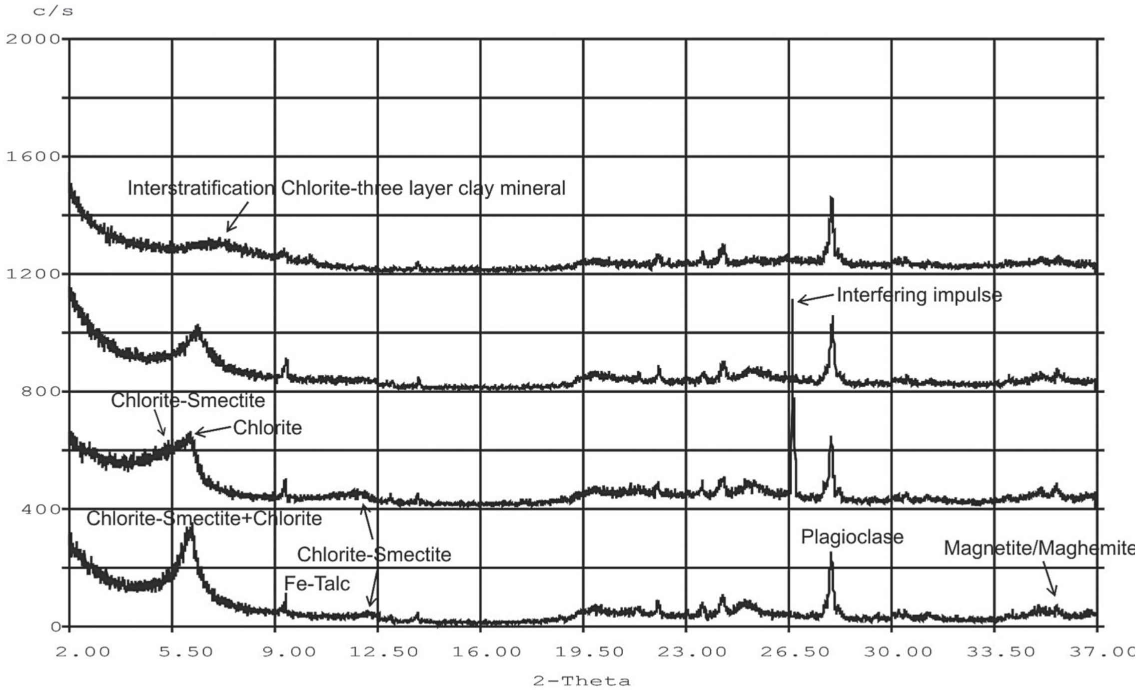


Fig. 21: Mineralogical composition of sample 3 (location no. 9 in Fig. 25, 1.6 m below surface). For the weak chlorite-smectite reflection near 12° 2-Theta, the contribution of a small amount of kaolinite-smectite cannot be excluded.

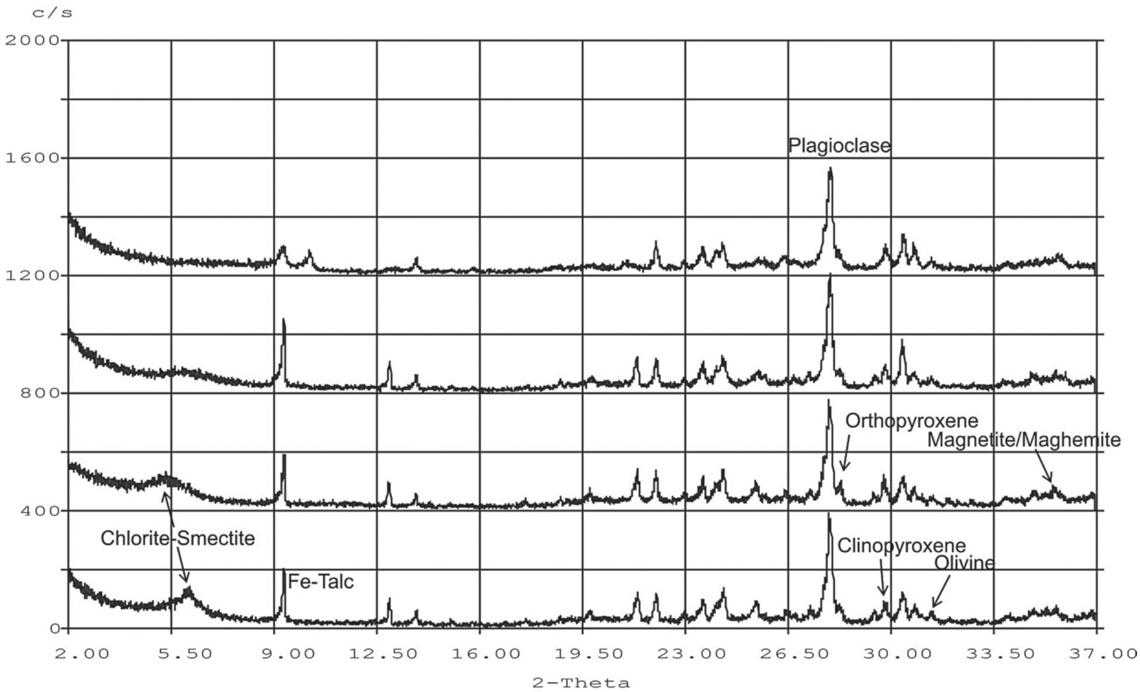


Fig. 22: Mineralogical composition of sample 4, basaltic parent rock, probably altered by diagenetic or hydrothermal processes (location no. 9 in Fig. 25, 2.2 m below surface).

in the quartz-bearing weathering products. Similarities to the quartz-bearing weathering products exist in the presence of gibbsite, goethite, hematite and amphibole (near the surface of some profiles). Also, disordered kaolinite sometimes occurs in addition to interstratified kaolinite-smectite. The most complete profile, from an auburn-coloured lateritic soil down to a fine-grained basalt as parent rock, yielded excellent results concerning the change of mineralogical and chemical composition during weathering (location no. 9 in Fig. 25, samples taken from 0.2 m, 0.6 m, 1.6 m, and 2.2 m below surface). However, the structure of this profile seemed to be disturbed. The X-ray diffraction patterns of this profile are shown in the Figures 19 to 22. Figure 19 (sample 1, 0.2 m) represents the most weathered part, consisting of kaolinite, interstratified kaolinite-smectite (with smectite layers showing chloritisation), gibbsite, hematite, goethite and traces of magnetite/maghemite. Traces of quartz occurring in this sample might come from aeolian input or caused by heavy downpours which erode soil material from higher elevations. Sample 2 (Fig. 20, 0.6 m) shows similar mineralogical composi-

Fig. 23: Geochemical weathering trends of the profile at location no. 9 (see Figs. 19-22).

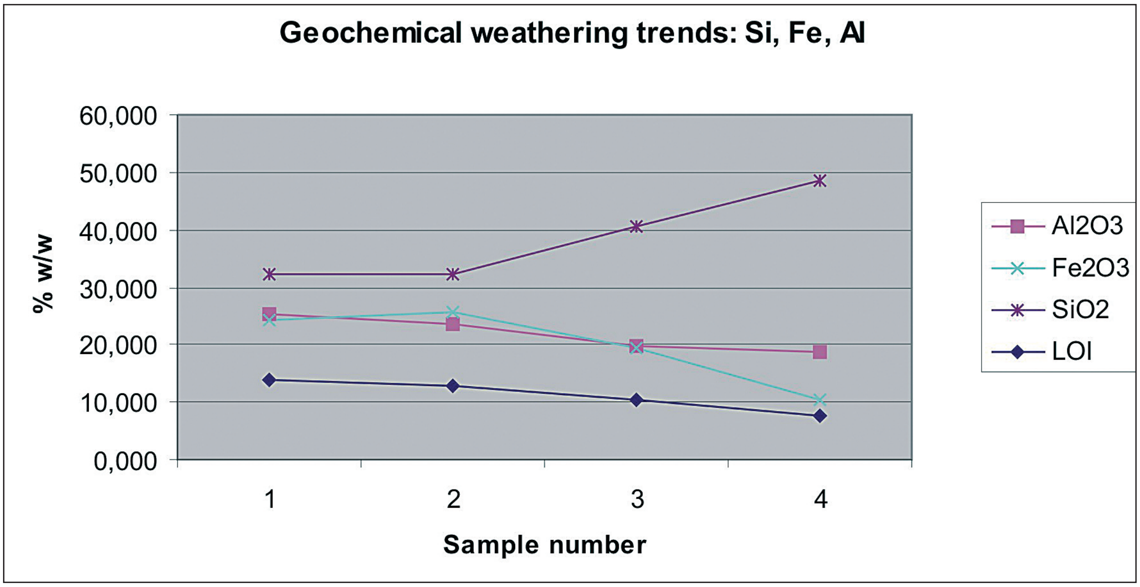
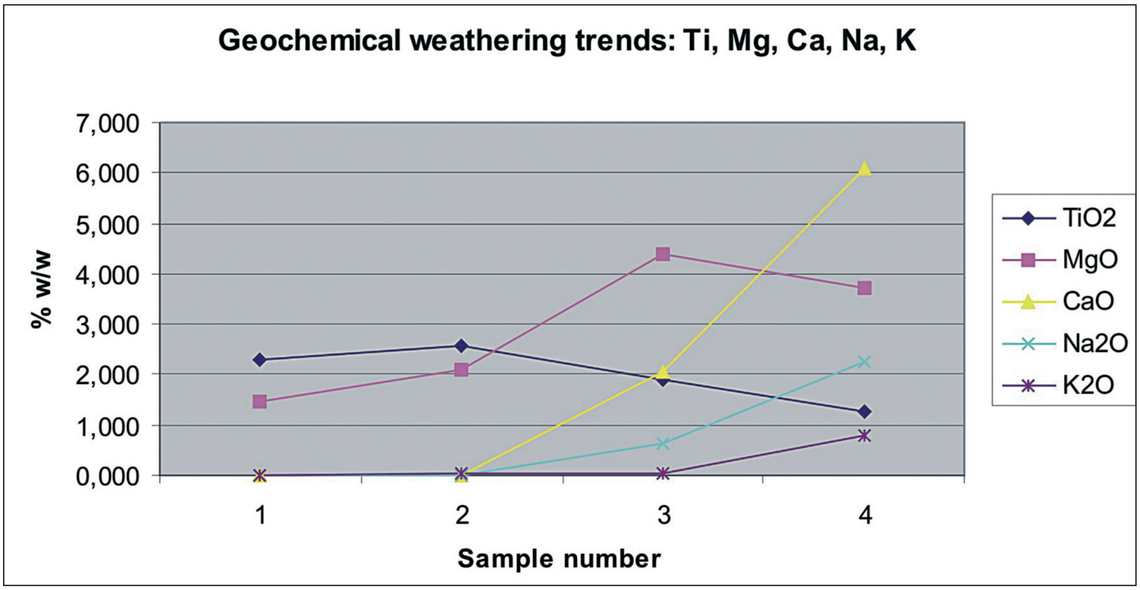


Fig. 24: Geochemical weathering trends of the profile at location no. 9 (see Figs. 19-22).



tion with the additional occurrence of weakly defined chlorite-smectite (interstratified), probably formed by (partial) chloritisation of smectite. Figure 21 (sample 3, 1.6 m) already shows some mineral phases of the parent rock (plagioclase, iron-rich talc, see below). Smectite, eventually formed during diagenesis or by hydrothermal action, might be inherited from the parent rock (sample 4, Fig. 22) as well. However, the relatively heat stable (nonexpandable) chloritic mineral of sample 3 does not occur in the lowermost sample (Fig. 22). It is probably the product of chloritisation of some (possibly expandable) hydrated three-layer clay mineral. Figure 22 (sample 4) represents the parent rock, a fine-grained basalt with the lowest degree of weathering. In this rock iron-rich talc, as in the sample of basic tuff (Fig. 8), and possibly smectite (here already partially chloritised) indicate hydrothermal influence.

Considering Figures 19 and 20, it can be seen that summing all mineral phases appearing in the X-ray diffraction patterns does not yield values near 100%. So, other mineral phases which can not be detected by XRD analysis must be present in these quartz-free weathering products. These so called "X-ray amorphous" phases are predominantly allophanes (clay minerals lacking distinct lattice order) and amorphous Al-hydroxides. Similar mineral phases are described by VORTISCH (1990) and KAUTZ & RYAN (2003) in other regions of Costa Rica.

XRF analyses of the four samples from the profile of location no. 9 (Figs. 19-22) show the typical trends for humid tropical weathering: depletion of CaO, MgO, K_2O, Na_2O and even SiO_2. The decrease in SiO_2 depends on the formation of new mineral phases during tropical weathering (predominantly clay minerals, allophanes and various oxides and hydroxides), because

these phases have lower SiO_2 contents than the average parent rock. A corresponding increase in TiO_2, Al_2O_3 and Fe_2O_3 contents could be detected from the unweathered basalt upward to the lateritic weathering product. This is also a typical trend for intensive tropical weathering as these elements are considered to be practically immobile in warm humid climates. The diagrams exhibiting the chemical trends discussed above are shown in Figures 23 and 24. LOI (loss on ignition) describes the loss of weight after heating to 1000°C (sample pre-dried at 105°C). The higher values in samples one and two correspond to the significantly higher clay mineral content (including X-ray amorphous phases) in these two samples.

Summary and Conclusions

The primary lithologies (green tuffites, brown basic tuffs, basalts, basaltic breccias and the sediments of the sequence of location no. 5) can be attributed to regional geology and stratigraphy (Golfito Terrain, according to DiMarco 1994) as follows: The green tuffites (1.1) and the brown basic tuffs (1.2) are supposed to be part of the "Fila Gamba Member" (the uppermost unit of the "Quebrada Achiote Formation"). Within this member, DiMarco (1994) reports the occurrence of fine-grained, green tuffites intercalated with primary pyroclastics (tuffs). Due to a likely Paleocene age of this member (see Fig. 2), the sedimentary sequence (1.3) cannot be attributed to this unit, because the limestone within this sequence indicates a Cretaceous age. Minor occurrences of pelagic limestones are reported from the middle part of the "Quebrada Achiote Formation", while they are much more frequent in the "Golfito Formation". Whether the sedimentary sequence belongs to the lower part of the Quebrada Achiote Formation (Upper Cretaceous) or to the Golfito Formation cannot be stated with certainty. This uncertainty has to be extended to the basalts and basaltic breccias (1.4). Basalts occur in the igneous basement and within the Golfito Formation. Basaltic breccias occur in the middle and lower parts of the Quebrada Achiote Formation and, to a lesser extent, in the Golfito Formation.

With exception of the limestone at location no. 5, all lithologies described here document intensive volcanic influence. Besides the occurrence of pure volcanoclastics (basic tuff), all siliciclastic sedimentary lithologies (green tuffite, clastic sediments of the sequence at location no. 5) show considerable volcanoclastic input. The volcanoclastic components of these siliciclastic sediments were diagenetically transformed into smectite, illite-smectite (interstratified) and, less frequently, zeolite. The presence of interstratified kaolinite-smectite in some lithologies points to the beginning of weathering. The basic character of the volcanoclastic components is indicated by the occurrence of plagioclase and pyroxene. Quartz represents a clastic component which was added to the volcanoclastics during redeposition. Only those volcanoclastic deposits that were not affected by redeposition, i.e. the basic tuffs, are essentially quartz-free.

The occurrence of glauconite and radiolarians in the green tuffites as well as the pelagic wackestone (location no. 5) prove the predominance of a marine depositional environment. This can also be concluded from the alteration of the volcanic breccia (albitisation of plagioclase, formation of analcime and calcite cement).

Samples from one outcrop of the basic tuff (location no. 3 in Fig. 25) and from an adjacent one in basalt (location no. 9 in Fig. 25) contain an iron-rich talc mineral. This mineral might prove a regional hydrothermal influence in this area.

The quartz-bearing weathering products are generally developed on green tuffites, which is indicated by fragments of these tuffites in deeper parts of corresponding profiles. The parent rock of the quartz-free weathering products could not be identified with certainty, because it was not possible to reach the parent rock and no rock fragments were found in the profiles. In this case all quartz-free rocks, i.e. basic tuffs, basalts, and basaltic breccias, are possible parent rocks for these weathering products. The differences between the two types of weathering products are clearly noticeable, especially with respect to the quartz content. Thus, subsurface lithology can at least partly be detected by the mineralogy of their soil cover.

The dominant clay mineral phase in the weathering products is interstratified kaolinite-smectite, with dominance of kaolinite layers, whereas kaolinite, the typical product of humid tropical weathering conditions occurs only in the uppermost parts of some profiles with considerable proportions. Halloysite, another typical clay mineral for humid tropical weathering conditions, is absent. The occurrence of this hydrated 1:1 clay mineral is reported by e.g. Vortisch (1990) and Kautz & Ryan (2003) in other regions of Costa Rica. The reason for the absence of halloysite in the study area is probably the climate. Halloysite can only be formed and preserved under constant humid conditions. The Pacific side of Costa Rica, on the other hand has distinct rainy and dry seasons (Weissenhofer & Huber 2001).

Gibbsite, an indicator of very intensive weathering, was only detected in topographically elevated areas. A dependence between weathering intensity and topography was already stated by Pamperl (2001b, pp. 28): "In ravines and lower slopes, soils are younger and less

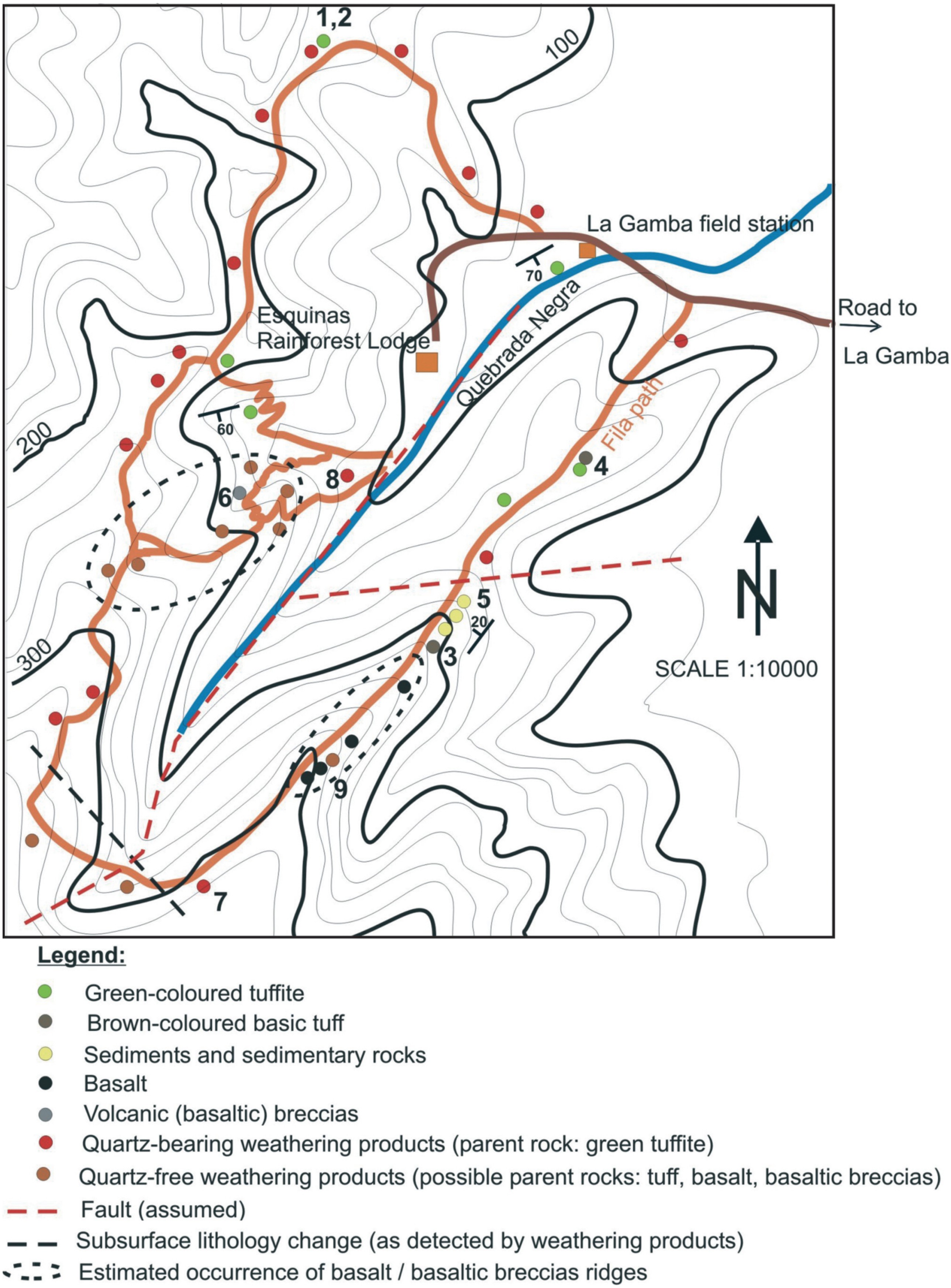


Fig. 25: Primary lithologies and weathering products in the investigated area with position of samples described in the text (coloured dots: outcrops and trenches of the corresponding lithologies resp. weathering products).

weathered. Only on the ridges and the upper slopes the old clay soils still remain." Moreover, the effect of more intensive drainage (leaching) in elevated areas might be of importance (MILLOT 1970).

Figure 25 provides a map of the study area with all described outcrops and profiles. Due to the generally thick soil cover, no fault could be observed in the field. The faults drawn in Figure 25 are assumed on the basis of morphology, because faults tend to promote intensively the formation of typical erosional landforms, which can be identified on topographical maps. Certainly, the Quebrada Negra follows a SW-NE striking fault, which is a relatively common direction of strike in the Golfo Dulce region (MALZER 2001).

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